Bridging 12 V and 48 V in dual-battery automotive systems

How a bidirectional buck-boost controller helps support a dual-bus topology

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The 12 V lead-acid battery system has met its match. With increasingly strict emission regulations, growing power load requirements of advanced automotive electronics and the conversion from mechanical components to electronic functions, the traditional automotive battery of choice has reached its current-carrying capacity.

In response, automakers and their suppliers have developed a second, additional electrical system at 48 V which delivers more power at lower currents than a traditional 12 V battery can produce alone.

The 48 V answer to 12 V limits

The new configuration consists of two separate branches. The traditional 12 V bus uses a conventional lead-acid battery for customary loads such as infotainment, lighting and windows; while the new 48 V system can support heavier loads such as starter generator units, air-conditioning compressors, active chassis systems, electric superchargers, turbochargers and regenerative braking.

As shown in **Figure 1**, a bi-directional power supply bridges the 12 V and 48 V systems. The result is a lighter-weight vehicle that's more fuel efficient and emits less carbon dioxide.

The 48 V system saves weight in the wiring harness. A higher voltage allows for smaller wire gauge, which reduces cable size and weight without sacrificing performance; today's high-end vehicles can have more than 4 km of wiring.

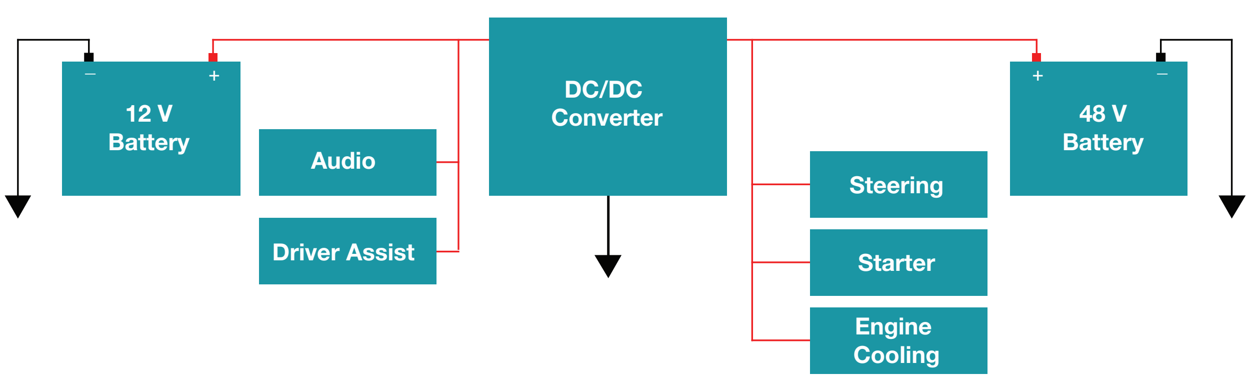

Figure 1. *How a 48 V electrical system supports the traditional 12 V system.*

Along with the traditional 12 V battery, a 48 V lithium-ion battery or a supercapacitor and a bidirectional DC/DC converter round out the dual-battery system to deliver up to 10 kW of available power. Bidirectional power transfer is required to charge either battery if it's discharged and to provide extra power for the opposite voltage rail in an overload condition.

In this white paper, I will discuss the requirements of a 12 V/48 V system and look at an innovative average current-mode control scheme using TI's LM5170-Q1. This buck/boost controller implements all control circuitry for bidirectional energy conversion, making systems significantly simpler compared to traditional discrete implementations.

LV 148: the starting point

The LV 148 standard for 48 V-battery automotive systems specifies that the maximum voltage on a 48 V rail must reach up to 70 V for at least 40 ms. Additionally, the system must remain functional without any loss of performance during such an overvoltage event. For semiconductor suppliers, this means that everything connected to a 48 V rail must withstand 70 V on the input. The automotive industry considers a safety margin of 10% or more; to meet this expectation, components on an unprotected 48 V rail should be rated for 100 V.

For power transfer from the 48 V rail to the 12 V rail you can use a buck converter, while power transfer in the 12 V to 48 V rail direction is achievable with a boost converter. The buck and boost topologies are well-known in power electronics, but designing two separate converters will take up valuable board space and increase system complexity and cost.

Design engineers typically manage 12 V and 48 V dual-battery systems using a digital control scheme, which includes multiple discrete components such as current-sense amplifiers, gate drivers and protection circuits. As an alternative, TI offers a mixed architecture in which the microcontroller (MCU) handles higher-level intelligent management and an integrated analog controller such as the LM5170-Q1 provides the power conversion. The LM5170-Q1 can also be implemented in a pure analog function, removing the MCU from the loop.

The LM5170-Q1 efficiently transfers electric power greater than 500 W per phase between dual 48 V and 12 V automotive battery systems and provides integrated current-sense amplifiers and high-current gate drivers. System protection features include an integrated circuit breaker and independent phase-current monitoring, which eliminate additional discrete components. Stacking multiple controllers in parallel enables the delivery of kilowatts of power; the 48 V bus can provide up to about 10 kW of power for driving various systems, as shown in **Figure 2**.

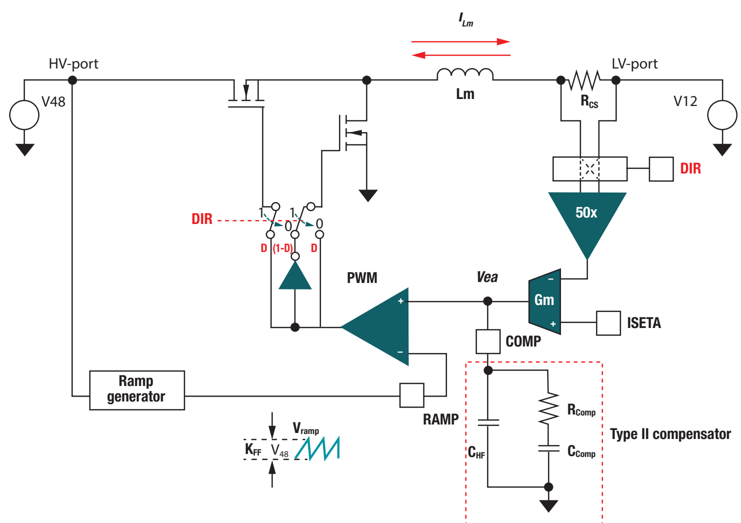

Figure 2. *A current control loop of the LM5170.*

TI's average current-mode control scheme regulates the average current flowing between the high- and low-voltage ports in a direction designated by a direction input response (DIR) signal. When setting DIR to "1," power flows from the 48 V port to the 12 V port. When setting DIR to "0," power flows from the 12 V port to the 48 V port. The DIR command defines how the LM5170-Q1 controls Q1 and Q2 in either buck or boost mode.

A conventional average current-mode control scheme presents two challenges: the current-loop transfer function varies with the operating voltage and current conditions, and bidirectional operation requires two different loop compensations. Within TI's LM5170-Q1, the transfer function is the same for bidirectional operation. Since the TI solution maintains a constant-loop gain, it allows a single resistor-capacitor (RC) network to compensate for both buck and boost conversion.

Advantages of the TI control scheme

- High accuracy: The controller's 1% accurate bidirectional current regulation ensures precise power transfer.
- Power efficiency: The LM5170-Q1 allows for system efficiency greater than 97%.
- High precision: The controller monitors current with up to 99% accuracy.
- High power: Integrated 5 A peak half-bridge gate drivers provide high-power capability.
- Superior performance: The diode emulation mode of the synchronous rectifier metal-oxide semiconductor field-effect transistors (MOSFETs) prevents negative current and enhances light-load efficiency.
- Automotive quality: The LM5170-Q1 is Automotive Electronics Council (AEC)-Q100 qualified.

Table 1 outlines features to consider in a 48 V system.

Features	Voltage mode	Peak-current mode	Conventional average - current mode	TI Proprietary average - current mode (LMS5170-Q1)
Good noise immunity for all load conditions	✔		✔	✔
First-order system, easy to compensate		✔	✔	✔
Supports multiphase parallel operation		✔	✔	✔
No need for slope compensation	✔		✔	✔
Excellent DC current regulation regardless of power inductor tolerances			✔	✔
Constant current-loop gain regardless of voltage and load conditions				✔
Single compensation stabilizing bidirectional operation, regardless of operating conditions				✔

Table 1. *Comparing the features of the LM5170-Q1 control scheme.*

The simplified application circuit, as shown in **Figure 3**, displays the integrated nature of the LM5170-Q1.

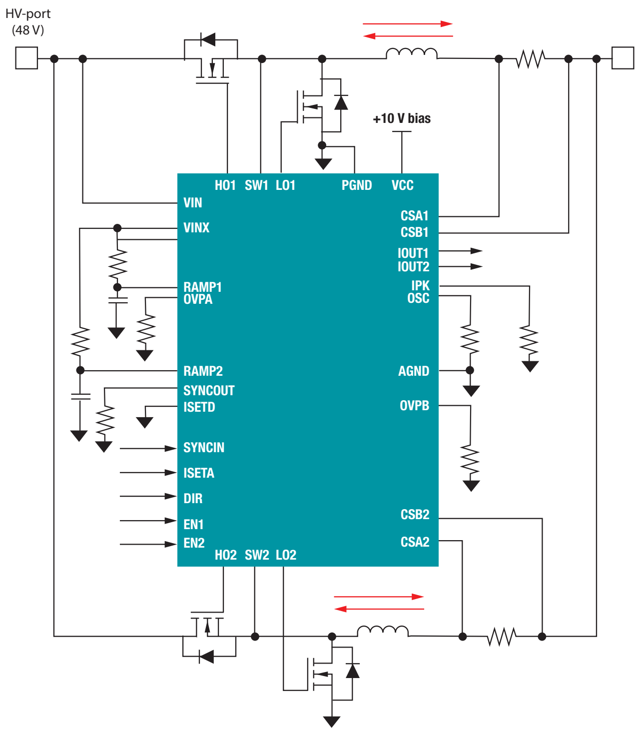

Figure 3. *A simplified application circuit.*

On the LM5170-Q1 controller, analog signal or digital pulse-width modulation (PWM) inputs program the current regulation level. Dual-channel differential current-sense amplifiers and dedicated channel current monitors achieve a typical accuracy of 1%. The 5 A half-bridge gate drivers are capable of driving parallel MOSFET switches, delivering typically 500 W or more per phase. The diode emulation mode of the synchronous rectifiers prevents negative currents and improves efficiency in discontinuous mode operation during light loads. Protection features include cycle-by-cycle current limiting, overvoltage protection at both high- and low-voltage ports, MOSFET failure detection, and over-temperature protection.

Power stage and control circuit

The average current-mode control scheme for 48 V-12 V bidirectional converter operation has a power stage consisting of:

- A high-side FET (Q1).
- A low-side FET (Q2).
- A power inductor (LM).
- A current-sense resistor (RCS).
- Two batteries: one at the high-voltage port and one at the low-voltage port.

The control circuit includes:

- A current-sense amplifier with a gain of 50 with direction steering by the DIR command (0 or 1).
- A transconductance amplifier serving as the current-loop error amplifier, with a reference signal (ISET) applied at the noninverting pin to set the phase DC current-regulation value.
- A PWM comparator.
- A ramp signal generated in proportion to the high-voltage port.
- A steering circuit controlled by DIR to apply the PWM signal to control either Q1 or Q2 as the main switch.
- A loop compensation network at the COMP node.

A 48 V-12 V bidirectional converter normally requires highly accurate current regulation (better than 3%) to precisely control the amount of power delivered from one battery rail to the other. Owing to high power, the system usually requires multiphase circuits in an interleaved parallel operation to share the total load, and sharing should be evenly balanced among individual phases. For this reason, a voltage-control mode topology is not suitable because of its inability to achieve multiphase sharing.

The LM5170-Q1 enables multiphase parallel operation by synchronizing multiple controllers for a higher number of phases. Each phase synchronizes to a phase-shifted clock. Using a multiphase architecture reduces the physical size of components and makes thermal management easier. To easily parallel each power phase, the control scheme in either buck- or boost-mode operation is current-mode control. Multiphase operation also enables interleaved switching of each phase, reducing output ripple and thus electromagnetic interference (EMI).

Finally, with two batteries in play, there is a heightened chance that one or both car batteries will be detached and reconnected during maintenance. During reconnection, it's possible to connect the wires to the wrong battery terminals, which can damage the components in the ECUs. Avoiding this type of damage requires reverse polarity protection. You cannot use Schottky diodes because of their high power loss. Instead, the LM5060-1-Q1 high-side circuit-breaker controller along with an n-channel MOSFET reduces the power dissipation. The LM5050-Q1 operates in conjunction with the external MOSFET as a diode rectifier when connected in series with a power source. It can connect power supplies ranging from 5 V to 75 V and withstand transients as high as 100 V.

Conclusion

The LM5170 48 V-12 V bidirectional converter evaluation module (EVM) is designed to showcase the LM5170-Q1 controller. You can control the direction of power flow through either an external command signal or the onboard jumper. Through the onboard interface headers, you can operate the EVM with a digital signal processor (DSP), field-programmable gate array (FPGA), MCU or other digital controllers. Paralleling two or more EVMs creates a multiphase interleaved converter for higher power.

In addition, the Bidirectional DC/DC converter reference design for 12 V/48 V automotive systems fulfills the typical operating voltage requirements for 12 V/48 V automotive systems. The system uses two LM5170-Q1 current controllers and a C2000™ TMS320F28027F MCU for power-stage control, providing voltage feedback to the system.

TI's 12 V/48 V solution provides current control using an innovative average current-control scheme that eliminates additional phase-current balancing circuitry, which is typical for multiphase converters. The LM5170-Q1 brings a high level of integration, which reduces printed circuit board (PCB) area, simplifies design and speeds up development.

Additional resources

- Learn more about automotive systems at TI.
- Read the white paper, "Driving the green revolution in transportation."

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